The SM extension with color-octet scalars: diphoton enhancement and global fit of LHC Higgs data Postprint

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Preamble

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The SM extension with color-octet scalars: diphoton enhancement and global fit of LHC Higgs data
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Abstract

In light of the significant progress of the LHC in determining the properties of the Higgs boson, we investigate the capability of the Manohar-Wise model to explain the Higgs data. This model extends the SM by one family of color-octet and isospin-doublet scalars, and it can sizably alter the coupling strengths of the Higgs boson with gluons and photons. We first examine the current constraints on the model, which arise from unitarity, LHC searches for the scalars, and electroweak precision data (EWPD). In implementing the unitarity constraint, we use properties of the SU(3) group to simplify the calculation. Then, in the allowed parameter space, we perform a fit of the model using the latest ATLAS and CMS data, respectively. We find that the Manohar-Wise model is able to explain the data with ^{2} significantly smaller than the SM value. We also find that the current Higgs data, especially the ATLAS data, are very powerful in further constraining the parameter space of the model. In particular, in order to explain the $\gamma\gamma$ enhancement reported by the ATLAS collaboration, the sign of the hgg coupling is usually opposite to that in the SM.

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Introduction

Based on approximately 25 fb^{-1} of data collected at 7-TeV and 8-TeV LHC, the ATLAS and CMS collaborations have further confirmed the existence of a new boson with local statistical significance reaching 9σ and more than 7σ, respectively [1–4]. Thus far, the mass of the boson has been rather precisely determined to be around 125 GeV, and its other properties, albeit with large experimental uncertainties, agree with those of the Higgs boson in the Standard Model [4, 5]. Since such a Higgs-like boson should play a role in electroweak symmetry breaking and mass generation, its discovery is widely considered a great success of the LHC and marks a milestone in understanding the mechanism of electroweak symmetry breaking.

On the other hand, this discovery also poses new questions. For example, as the experimental precision in determining the properties of this Higgs-like boson has improved significantly, it is urgent for theorists to investigate the nature of this boson, especially its role in electroweak symmetry breaking and mass generation. To answer these questions, various methods have been proposed to extract physical information about this boson from LHC data [6–12], which showed that the current data, particularly the sizable deviation of the $\gamma\gamma$ signal from its SM prediction [13, 14], favor new physics interpretations. This conclusion makes it important to explore the properties of the Higgs boson in various new physics models.

As the simplest modification of the SM Higgs sector, the two-Higgs-doublet model has been extensively studied for almost thirty years. In its traditional realization (called T2HDM hereafter), the model extends the SM by one family of color-singlet and weak-doublet scalars. As a result, the model respects custodial symmetry in a natural way, avoids tree-level flavor-changing neutral current (FCNC) by imposing a discrete Z_2 symmetry, and has interesting collider phenomenology due to its rich scalar sector spectrum. Because of these attractive features, analyses of Higgs data in the T2HDM have been carried out since the first hint of the Higgs boson at the LHC was released at the end of 2011 [15–22]. These studies, however, indicate that the T2HDM is not much better than the SM in explaining the data (extensions with new particles [17] or the aligned T2HDM [18] may be exceptions). For example, in its most popular type-I and type-II versions, it has been shown that, after considering various experimental and theoretical constraints, the T2HDM can explain the LHC data only at the 1σ level in a very narrow parameter space [21], and the global minimum of ² is roughly equal to the SM value [22]. Confronted with this situation, we investigate in this work the prospect of explaining the Higgs data in another type of two-Higgs-doublet model, usually called the Manohar-Wise model [23]. This model, well-motivated by the principle of minimal flavor violation, extends the SM by one family of scalars in the $(8, 2)_1/_2$ representation under the SM gauge groups. It retains the virtues of the T2HDM but may explain the data more flexibly. Specifically, in the T2HDM the only way to influence Higgs signal rates at the LHC is by modifying the decay rates of the Higgs boson [15, 16, 18–21], while the Manohar-Wise model can also alter the Higgs production rate at the LHC by changing the Higgs coupling with gluons. Although this feature has been noticed before [24–29], a systematic study of Higgs properties in the Manohar-Wise model has not been performed.

It should be emphasized that color-octet scalars are well-motivated in many fundamental theories, such as various SUSY constructions [30], topcolor models [31], and models with extra dimensions [32]. Meanwhile, their phenomenology has been studied comprehensively. For example, single and pair production of these scalars at the LHC were studied in [33, 34], their implications for Higgs phenomenology were investigated in [24–29], and they were also utilized to explain the 'Wjj' anomaly observed by CDF [35]. In this work, we investigate the capability of the Manohar-Wise model to explain the Higgs data. To this end, we first examine the theoretical and experimental constraints on the model, which arise from unitarity, LHC searches for these scalars, and electroweak data. Then we perform a fit to the current Higgs data. In implementing the unitarity constraint on the model, we use properties of the SU(3) group to simplify the calculation. This method, to our knowledge, has not been considered before.

The outline of the paper is as follows. In Section II, we briefly review the Manohar-Wise model, and in Section III we discuss the unitarity and collider constraints on the model. A fit of the model to the current Higgs data is performed in Section IV, and the behavior of the model in explaining the data is illustrated. Finally, we present our conclusion in Section V.

II. The Manohar-Wise Model

Motivated by the principle of minimal flavor violation, the Manohar-Wise model extends the SM by one family of color-octet scalars in the $(8, 2)_1/_2$ representation of the gauge group SU(3)C SU(2)L U(1)Y [23]. The explicit form of the scalars is given by S = S T , where A = 1, ···, 8 is the color index, S^+ denotes an electrically charged color-octet scalar field, and R, I are neutral CP-even and CP-odd ones, respectively. To avoid tree-level FCNC, the Yukawa couplings of these scalars with SM fermions are usually parameterized as

L = - Y ū S Q - Y R̄ (S)†Q + h.c.,

where Y , are the SM Yukawa matrices with i, j denoting flavor indices, and , are flavor-universal constants.

The most general renormalizable scalar potential is given by [23]

V = m^2H† H + λ(H† H $)^2$ + 2m ^{2}Tr(S† S) + λ_1H† H Tr(S† S) + λ_2H† H Tr(S† S) + λ_3H† H† Tr(S S) + λ_4H† Tr(S† S S) + λ_5H† Tr(S† S S) + h.c. + λ_6Tr(S† S S† S) + λ_7Tr(S† S S† S) + λ_8Tr(S† S)Tr(S† S) + λ_9Tr(S† S)Tr(S† S) + λ_{10}Tr(S S)Tr(S† S†) + λ_{11}Tr(S S S† S†),

where S = S T with the color index A summed, i, j denote isospin indices, and all λ (i = 1, ···, 11) except λ_4 and λ_5 are real parameters [23]. Note that by choosing an appropriate phase of the S multiplet, the convention $\lambda_3 > 0$ is allowed. From this potential, one can easily obtain the mass spectrum of the scalars

M$\pm^2$ = m ^{2} + $\lambda_1 v^2$, M ^{2} = m ^{2} + (λ_1 + λ_2 + 2λ_3)v^2, M ^{2} = m ^{2} + (λ_1 + λ_2 - 2λ_3)v^2,

and their interactions with the color-singlet Higgs boson h (h corresponds to the SM Higgs boson) [36]

g = -2iλ vδ ,

where i = ±, R, I, and we define λ± = λ_1, λ , = ½(λ_1 + λ_2 ± 2λ_3).

Regarding the Manohar-Wise model, two points should be noted. First, just like the W boson in the SM, S± can contribute to low-energy flavor-changing processes such as b → sγ, and to escape the corresponding experimental constraints, small | | is favored [23]. The importance of and is that they determine the decay pattern of the scalars and consequently affect their searches at colliders [34, 37]. Second, although the Yukawa couplings of h with fermions and weak bosons in the model are the same as those in the SM, the couplings of h with gluons, photons, and Zγ may be changed greatly by S-mediated loops. Explicitly, in the Manohar-Wise model these couplings are given by [38]

C /SM C /C ^{SM} = 1 + (C)±/C ^{SM}, C gg/SM C gg/C gg^{SM} = 1 + Σ =±,R,I (C gg) /C gg^{SM}, C Z /SM C Z /C Z ^{SM} = 1 + (C Z)±/C Z ^{SM},

where (C XY/C XY^{SM}) with X, Y = g, γ, Z denotes the contribution of S (i = ±, R, I) to the normalized hXY interaction, and A_0, $A_1/_2$, A_1, C_0, $C_1/_2$, and C_1 are loop functions defined in [39] with τ = m ^{2}/4M ^{2} and = mZ^2/4M ^{2}. As a result, the decay width of h → XY is now given by [25]

Γ → = G α^2m ^{3}/(64√2π^3) |A_1(τ) + $A_1/_2$(τ) + (8/3)$A_1/_2$(τ) + Σ =±,R,I λ v^2/M ^{2} A_0(τ)$|^2$, Γ →gg = G α ^{2}m ^{3}/(36√2π^3) |$A_1/_2$(τ) + Σ =±,R,I (3λ v^2/2M ^{2}) A_0(τ)$|^2$, Γ →Z = G m ^{3}α/(32√2π^3) (1 - mZ^2/m $^2)^3$ |C_1(τ $^{-1}$, $^{-1}$) + (1 - 2$\sin^2$)/cos C_0(τ $^{-1}$, $^{-1}$) + 2λ±v^2/M$\pm^2$ (1 - 8/3 $\sin^2$)/cos C_0(τ$\pm^{-1}$, $\pm^{-1}$)$|^2$.

Note that our expression for (C Z)± differs from the formula in [39] by a minus sign. Such a typo in [39] was recently pointed out in [40].

Finally, we remind that in the limit M± v and moderate mass splitting of S± with S , , the forms of the equations can be greatly simplified:

(C gg/SM)± 1 + 2.3 × (λ_1 ± λ_3)v^2/M±^{2}, (C gg/SM) 1 + 1.149 × (λ_1 + λ_2 + 2λ_3)v^2/M±^{2}, (C gg/SM) 1 + 1.149 × (λ_1 + λ_2 - 2λ_3)v^2/M±^{2}.

These approximations are very helpful for our later understanding.

III. Constraints on the Manohar-Wise Model

A. Unitarity Constraint

In theories with electroweak symmetry breaking, the unitarity constraint plays an important role in limiting their scalar sector. This constraint arises from the optical theorem and requires that the partial waves in scattering processes involving scalars and/or vector bosons satisfy |a | < 1 [41]. In actual calculations of pure scalar scattering processes $S_1S_2 \rightarrow S_3S_4$ in the high-energy limit, the J = 0 s-wave amplitude a_0 is approximated by [42]

a_0 Q/(16π),

where Q denotes the coupling strength for the four-point vertex $S_1S_2S_3S_4$, and the other partial wave amplitudes are relatively small. Thus, the unitarity constraint becomes $|Q| < 16\pi$.

For scattering processes involving vector bosons, in the high-energy limit the dominant contributions come from longitudinal polarized vector bosons. The equivalence theorem states that its amplitude can be approximated by the scalar amplitude in which the gauge bosons are replaced by their corresponding Goldstone bosons [43, 44]. Therefore, the formula for scalar scattering remains valid when implementing the unitarity constraint.

Regarding the unitarity constraint, another problem one must face is that the constraint $|a_0| < 1$ is valid for any scattering process S S → S S where S , S , S , and S represent arbitrary normalized combinations of the scalar fields in the theory, and one must find the largest value of $|a_0|$ to implement the constraint. In general, this can be achieved by choosing a set of basis vectors, such as {S_1S_1, S_1S_2, ⋯} with S denoting the fields in the original Lagrangian, arranging the s-wave amplitudes for scatterings S S → S S with i, j, k, l = 1, 2, ⋯ in matrix form, and then diagonalizing this matrix to obtain its eigenvalues [41, 42]. However, as far as the Manohar-Wise model is concerned, such a task is not easy because the model predicts 9 CP-even scalars (i.e., h and S), 9 CP-odd scalars, and 18 charged scalars, requiring one to deal with a matrix of 362 × 362 dimension. Here we point out that since the model preserves electric charge number and also maintains CP and SU(3) invariance, one can categorize the basis into subsets, each having definite CP and charge quantum numbers while transforming under a certain SU(3) representation.

Considering that the transition submatrices based on these subsets do not couple with each other due to these conservation laws, the whole matrix is blockdiagonal in submatrix space, which greatly simplifies the process of finding the eigenvalues. To be more specific, noting the decomposition rule of the tensor product in the SU(3) group:

$8 \quad 8 = 1 \quad 8 \quad 8 \quad 10 \quad \overline{10} \quad 27,$

we divide the bi-scalar system (which corresponds to the initial or final state in the scattering) into 1-, 8-, 8-, 10-, $\overline{10}$-, and 27-dimensional representations, respectively. In the appendix, we present the Clebsch-Gordan coefficients in the decomposition and the corresponding transition amplitudes for scattering processes with initial and final states lying in a certain SU(3) representation.

In this work, since only λ_1, λ_2, and λ_3 are relevant to our discussion, we study the unitarity constraint on them by setting other λ (i = 4, $\cdots$, 11) to zero. For the best-fit value m = 125.5 GeV [4, 5], we find $|\lambda_1|$, $|\lambda_2|$, $|2\lambda_1 + \lambda_2|$ 35 and λ_3 18. We note that our method can reproduce the formula in [45], which was obtained ten days later than our work. The difference is that in [45], the authors required $\mathrm{Re}(a_0) < 1/2$, while we require $|a_0| < 1$ as in [41].

B. Collider Constraints

In the Manohar-Wise model, the color-octet scalars are mainly produced in pairs at hadron colliders [34], and experimental efforts to search for them focus on dijet-pair events and four-top events. The former search channel is effective for , 0. In this case, the scalars are fermiophobic and at least the lighter neutral scalar will predominantly decay into gluon pairs through scalar loops [34]. Then the latest search for dijet-pair events at 7-TeV LHC, performed by the ATLAS collaboration based on 4.6 fb^{-1} of data, pushes the scalar mass above 287 GeV at 95% confidence level [46]. Note that this bound is significantly lower than that for a color-octet vector boson, which has now been pushed to about 740 GeV by the CMS collaboration [47]. The reason is that the cross section for scalar pair production is usually much smaller than that for a vector boson of the same mass.

The latter search channel is relevant if one of the neutral scalars dominantly decays into $\bar{t}t$, which can be achieved in the Manohar-Wise model through a sizable [37]. According to ATLAS analysis with about 4.7 fb^{-1} of data collected at 7-TeV LHC, the measurement of the same-sign dilepton event rate has placed an upper bound on the four-top-quark production cross section of 61 fb at 95% confidence level [48]. This bound corresponds to the requirement that the neutral scalar mass must be heavier than about 500 GeV (630 GeV) if the neutral scalar decays into $\bar{t}t$ with a branching ratio of 50% (100%). Since all these mass bounds depend on certain assumptions, we use a conservative mass limit of 300 GeV in our discussion.

Perhaps the more robust constraint on the exotic scalars comes from electroweak precision data (EWPD). The dominant way these scalars influence electroweak observables, such as S, T, and U variables, is through their contributions to the self-energy of the gauge bosons γ, Z, and W [49, 50]. In this work, we calculate these observables using the formulae presented in [51] and use the following experimental information to calculate the corresponding ^{2} [51]:

S = 0.03 $\pm$ 0.10,
T = 0.05 $\pm$ 0.12,
U = 0.03 $\pm$ 0.10,

with correlation coefficient matrix:

M_{STU} = [1, -0.54, -0.83; -0.54, 1, -0.83; -0.83, -0.83, 1].

We require ^{2} < 8.03, which corresponds to the 95% confidence region defined by the cumulative distribution function for the three-parameter fit, to limit the mass spectrum of the scalars. We find that the EWPD favor either of the following correlations:

- λ_2 $2\lambda_3$ or equivalently M$\pm$ M
- λ_2 -$2\lambda_3$ or equivalently M$\pm$ M

We note that the former case has been discussed in [50].

IV. Status of the Manohar-Wise Model Confronted with the Latest Higgs Data

In this section, we perform fits of the model to the latest Higgs data presented at the Rencontres de Moriond 2013 using the method first proposed in [7, 8] and recently recapitulated in [20]. These data include the measured signal strengths for $\gamma\gamma$, ZZ, *WW*, b̄b, and $\tau\bar{\tau}$ channels, and their explicit values are summarized in Fig. 2 of [5] (also Fig. 6 of this paper) for the ATLAS results and in Fig. 4 of [4] for the CMS results. In our fit, we calculate various observables in Higgs production processes at the LHC using the formulae given in Sect. II and [52] for fixed m = 125.5 GeV and m = 173 GeV, and we properly consider the correlations of the data as in [20]. Noting that, due to unknown systematics between the two experiments, the new CMS results in the $\gamma\gamma$ channel (0.78 $\pm$ 0.27 for mass-fit multi-variable analysis and 1.11 $\pm$ 0.31 for cut-based analysis [14]) are much smaller than their previous results ($1.56^{+0}.^{46}$ $_{0\cdot 42}$ [53]) and also smaller than the ATLAS measurement (1.6 $\pm$ 0.3 [5]), we do not combine the two experimental data sets. Instead, we perform two independent fits using the ATLAS data and the CMS data separately. We find that ^{2}/d.o.f. in the SM are 10.55/9 for the ATLAS data and 4.69/9 for the CMS data, while ^{2}{min}/d.o.f. *in the Manohar-Wise model are 5.63/5 and 2.47/5, respectively. Here the total number of d.o.f. is counted in a naive way as* = *n*{obs} - n_{para}, where n_{obs} and n_{para} denote the numbers of experimental observables and model free parameters, respectively, and for both experiments we use 9 sets of data. Note that in the Manohar-Wise model, ^{2} with the CMS data is much smaller than that with the ATLAS data, and so is the ^{2}_{min}. This is mainly because, for both collaborations, the same Higgs signal is usually measured in more than one production channel, and the CMS results are more consistent in the signal rates. Also note that similar fits with the latest Higgs data have been done in other new physics frameworks [21, 54, 55].

Our fit procedure is as follows. We first perform an extensive random scan over the parameter region:

300 GeV $\leq$ M , M , M$\pm$ $\leq$ 1500 GeV,
-40 $\leq \lambda_1$, $\lambda_2 \leq$ 40,
0 $\leq \lambda_3 \leq$ 20.

We keep the samples satisfying the unitarity constraint and the collider constraints. Then we calculate the ^{2} associated with each surviving sample and concentrate on two types: those with ^{2}{min} + 2.3 *(corresponding to 5.63 $\leq$ ^{2} $\leq$ 7.93 for the fit to ATLAS data and 2.47 $\leq$ ^{2} $\leq$ 4.77 for the fit to CMS data) and those with* ^{2}{min} + 2.3 $<$ ^{2} $\leq$ ^{2}_{min} + 6.18 (corresponding to 7.93 $<$ ^{2} $\leq$ 11.81 and 4.77 $<$ ^{2} $\leq$ 8.65, respectively). These two sets of samples correspond to the 68% and 95% confidence level regions in any two-dimensional parameter plane of the model to explain the Higgs data [20], and hereafter we call them 1σ and 2σ samples, respectively. Note that for most of the 1σ samples in the fit to CMS data and the 2σ samples in the fit to ATLAS data, they predict ^{2} smaller than the SM values. This reflects that the Manohar-Wise model is well-suited to explain the current LHC data.

[Figure 1: see original paper] shows scatter plots of the samples surviving different constraints, projected on the planes of λ_1, 2λ (= $\lambda_1 + \lambda_2 + 2\lambda_3$), and 2λ (= $\lambda_1 + \lambda_2$ - $2\lambda_3$) versus M , respectively. Here all samples satisfy the unitarity and collider constraints, while the red bullets and blue triangles in the upper (lower) panels represent samples that can further explain the ATLAS (CMS) data at 1σ and 2σ, respectively. This figure indicates that the LHC Higgs data are very effective in further limiting the parameter space that survives the unitarity and collider constraints, especially for the small M region. For example, at 68% confidence level both experiments disfavor a positive λ , and the ATLAS data also rule out the possibility of a positive λ_1. Another example: we once counted the number of 1σ samples in our random scan and found that in the fit to ATLAS data, it is only about 0.5% of the total samples that satisfy the unitarity and collider constraints, while in the fit to CMS data it is about 7%. This figure also indicates that, due to the great difference in the $\gamma\gamma$ rate between the two experiments, the parameter space favored by ATLAS is quite different from that favored by CMS. This fact makes it urgent for the two collaborations to further improve their measurements. Regarding Fig. 1, we checked that the lower borders of the sky-blue regions for M 950 GeV are determined by the scalar mass bound, and the other borders are mainly determined by the unitarity constraint. We also checked that the EWPD prefer the correlation λ_1 2λ or λ_1 2λ .

Considering that the ATLAS data changed little since last June and that in new physics models it is difficult to predict a significantly enhanced $\gamma\gamma$ rate relative to its SM prediction, we illustrate how the Manohar-Wise model can be used to explain the ATLAS data. We first project in [Figure 2: see original paper] the 1σ and 2σ samples from the upper panels of Fig. 1 onto the plane of C /SM versus C gg/SM, where C /SM and C gg/SM denote the h$\gamma\gamma$ and hgg couplings normalized to their SM values, respectively. In this figure, we also plot the central values (dot-dashed lines) and 1σ regions (bounded by dashed lines) of the $\gamma\gamma$ and ZZ* signal rates measured by the ATLAS collaboration [5]. As expected from the formula for ^{2} [7, 20], for each type of sample they should form an ellipse [56]. We checked that the missing parts of the ellipses are due to constraints from EWPD.

[Figure 2: see original paper] exhibits three distinct features. The first is that the sign of the hgg coupling tends to be opposite to that of the SM prediction, especially for the 1σ samples. The second is that the h$\gamma\gamma$ coupling may be enhanced by more than 50%, and even if we further require λ_1, λ , λ $< 8\pi$ as suggested by perturbation theory [57], it can still be enhanced by more than 30%. The last feature is that for most samples in Fig. 2, the magnitude of C gg/SM may exceed unity, which implies an enhanced ZZ* signal at the LHC relative to its SM expectation. This feature is unlikely to be realized in popular supersymmetric models [58, 59].

To explain these features, we hereafter consider only the 1σ samples of Fig. 2 and show in [Figure 3: see original paper] the correlation between the S$\pm$ and S contributions to the hgg coupling. We also fix M$\pm$ = 600 GeV and show in [Figure 4: see original paper] the correlations of different input parameters. From these two figures and the expressions in Eqs. (12), one can infer the following facts:

- As shown in the left and right panels of Fig. 4, in the Manohar-Wise model the EWPD prefer the degeneracy of M$\pm$ with either M (corresponding to $\lambda_1 = 2\lambda$ or $\lambda_2 = 2\lambda_3$) or M (corresponding to $\lambda_1 = 2\lambda$ or $\lambda_2 = -2\lambda_3$). In the case M$\pm$ M , c C gg/SM = 1 + (C gg/SM)$\pm$ + (C gg/SM) + (C gg/SM) 1 + 3/2(C gg/SM)$\pm$ + (C gg/SM) 1 + 2.3 $\times$ (λ_1 + λ_3)v^2/M$\pm^2$. In the case M$\pm$ M , c C gg/SM = 1 + (C gg/SM)$\pm$ + (C gg/SM) + (C gg/SM) 1 + 3/2(C gg/SM)$\pm$ + (C gg/SM) 1 + 2.3 $\times$ (λ_1 - λ_3)v^2/M$\pm^2$.
- Since the 1σ samples are characterized by $\lambda_1 < 0$ and $\lambda_3 > 0$, we have from Eqs. (12) that (C gg/SM)$\pm$ < 0, (C gg/SM) < 0, and (C /SM)$\pm$ -0.3(C gg/SM)$\pm$ > 0. As for (C gg/SM) and C gg/SM, they are positive only for the degeneracy M$\pm$ M and $\lambda_3 > |\lambda_1|$.
- For the degeneracy M$\pm$ M , to explain the ATLAS data at the 1σ level, c should be around either -1 or 1 (see Fig. 3). The former situation occurs for a negatively large λ_1 (and thus large negative (C gg/SM)$\pm$). In this case, the branching ratio for h $\to \gamma\gamma$ is greatly enhanced (see Fig. 3), and meanwhile the hgg coupling can be well-tuned by λ_3 (see the middle panel of Fig. 4). As a result, a rather low ^{2} can be obtained. For the situation c 1, it occurs only for small $|\lambda_1|$, consequently the branching ratio for h

$\to \gamma\gamma$ changes little, and ^{2} is usually large.

- For the degeneracy M± M , c should be around -1. Since in this case all scalar contributions to the hgg coupling are negative, the parameter λ_3 is not necessarily very large (see the middle panel of Fig. 4).
- At the turning point where the degeneracy M± M converts to M± M , $\lambda_3 = \lambda_2 = 0$. So as λ_1 becomes more negative from zero, λ_3 first decreases before reaching the turning point, then increases monotonously after departing from the point (see middle panel of Fig. 4). We numerically checked that this is true for M± 700 GeV. For M± 700 GeV, unitarity requires (λ_1 - λ_3) -17 for the degeneracy M± M , which implies C /SM 1 - 0.013 × λ_1 1.22 and C gg/SM 1 + 0.1 × (λ_1 - λ_3) -0.7. In such a situation, the turning point cannot be used to explain the ATLAS data at the 1σ level, which is why λ_1 is located in two separated regions (see upper left panel of Fig. 1).

As a complement to Fig. 2, we present details of the best-fit points in [TABLE:I] and compare their predictions on different Higgs observables with the corresponding experimental data in [Figure 5: see original paper]. This figure indicates that for the best point, most theoretical predictions agree with experimental data at the 1σ level, and the best explanations are achieved for the ATLAS results in $\gamma\gamma$ channels.

Noting that the decay h $\to$ Zγ was recently investigated both experimentally [60, 61] and theoretically [40, 62], we also examine the hZγ coupling in this work. In the Manohar-Wise model, this coupling receives new corrections only from S±-mediated loops, so the correction size depends on M± and λ_1. In [Figure 6: see original paper] we show such dependences. This figure indicates that, in contrast to possible large corrections from S± to the h$\gamma\gamma$ coupling, the S± correction to the hZγ coupling can only reach 17%. The reason is that the ZS^+S^- coupling strength is relatively small, i.e., C_{ZS}$^+$S$^-$ 0.3 C_γS$^+$S$^-$.

Like Figs. 2, 3, and 4, one may also investigate the features of the Manohar-Wise model in explaining the CMS data, but the situation is now quite complicated since for the 1σ samples in the bottom panels of Fig. 1, λ_1 may be either positive or negative. On the other hand, considering that the CMS data in 2013 are quite different from those in 2012, we prefer to wait for new data from the CMS collaboration before pursuing this further.

V. Conclusions

Since the discovery of the Higgs-like boson at the LHC, the experimental precision in determining its properties has improved significantly as more data have been accumulated. In light of this experimental progress, it is urgent for theorists to investigate how well new physics models can explain the data and what are the key features of the models in doing so. In this work, we attempt to answer these questions in the Manohar-Wise model.

As the first step of our research, we examine the constraints on the model, which include the unitarity constraint, collider searches for new scalars, and EWPD. In implementing the unitarity constraint, we note that it is a very complicated task in the Manohar-Wise model and has not been considered before, so we treat it in a special way. With the help of group theory, we succeed in solving this problem. Next, we perform a fit of the model by constructing an appropriate ^{2} function. Our fit procedure is as follows: we scan the parameter space of the model and retain only samples that satisfy various constraints; then, using the latest Higgs data released at the Rencontres de Moriond 2013, we calculate the ^{2} value associated with each surviving sample and determine the 68% and 95% confidence level regions in any two-dimensional parameter plane of the model to explain the Higgs data. In the calculation, we perform fits using data from the ATLAS collaboration and from the CMS collaboration separately, since due to unknown systematics the measured $\gamma\gamma$ and ZZ* rates of the two collaborations are quite different. Considering that in new physics models it is difficult to predict a significantly enhanced $\gamma\gamma$ rate, we also illustrate how the Manohar-Wise model is capable of achieving this.

Based on our analysis, we reach the following conclusions:

- The Manohar-Wise model is able to explain the ATLAS data and CMS data quite well, with resulting ^{2} significantly smaller than the corresponding SM ^{2}. In particular, to explain the $\gamma\gamma$ enhancement reported by the ATLAS collaboration, the sign of the hgg coupling is usually opposite to that in the SM.
- Current Higgs data, especially the ATLAS data, are very powerful in further limiting the parameter space of the model that satisfies unitarity and collider constraints. After considering all constraints, the degeneracy M± M or M± M is strongly preferred, and λ_1 is required to be less than 5 for M 500 GeV.

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Appendix A

In our method, the α-th state ($\alpha = 1, 2, \cdots, N$) of the bi-color-octet-scalar system (corresponding to the initial or final state in the scattering) in the N-dimensional representation of the SU(3) group is written as

B [α] = Σ_{A,B=1}^{8} S (C [α])_{AB}S ,

where C [α] denotes the Clebsch-Gordan coefficient for the decomposition in matrix form. When we talk about the basis (B $_1$, B $_2$, ⋯), it actually represents the collection of states (B $_1$[1], B $_2$[2], ⋯). On the other hand, because SU(3) symmetry is unbroken in the Manohar-Wise model, the transition amplitude for the scattering process B [α] → B ' [β] must take the form A δ ' δ_{$\alpha\beta$}, so without loss of information we can neglect the color index α of the basis and only investigate the dependence of A on model parameters. To present our formulae in a neat way, we define the following abbreviations:

$\lambda\{1,2\} = \lambda_1 + \lambda_2$,
$\lambda\{6,7\} = \lambda_6 + \lambda_7$,
$\lambda\{8,9\} = \lambda_8 + \lambda_9$,
$\lambda\{6,7,11\} = \lambda_6 + \lambda_7 + \lambda_{11}$,

and list only the expressions for non-zero scattering amplitudes.

1. Scatterings between states in 1-dimensional representation of the SU(3) group

In this case, the Clebsch-Gordan coefficients are given by C^1[1] = (1/2√2)δ_{AB}.

- Denoting A as the S-partial wave amplitude for the scattering B → B , with B and B representing any state in the basis {$\omega^-\omega^+$, zz/√2, hh/√2, (S^-S^+)$_1$, (S S)$_1$, (S S)$_1$}, we have:

$A_{11} = \lambda$,
$A_{12} = A_{13} = (1/4)\lambda$,
$A_{14} = (1/4)\lambda$,
$A_{15} = A_{16} = (1/4)\lambda_1$,
$A_{22} = A_{33} = (3/4)\lambda$,
$A_{23} = (1/4)\lambda$,
$A_{25} = A_{36} = (1/4)\lambda_1$,
$A_{26} = A_{35} = (1/4)\lambda_1$,
$A_{34} = (1/4)\lambda_1$,
$A_{44} = (1/2)(\lambda\{6,7\} + 4\lambda_1 + 2(\lambda_2 + 2\lambda_3))$,
$A_{45} = A_{46} = (1/4)\lambda_1$,
$A_{55} = A_{66} = (1/2)(\lambda\{8,9\} + \lambda_{10} + (7/6)\lambda_{11})$,
$A_{56} = (1/2)(\lambda_1 + \lambda_2 - \lambda_3)$,
$A_{66} = (1/2)(\lambda\{6,7,11\} + (5/4)\lambda_1 + \lambda\{8,9,10\})$.

- In the basis {hz, (S S)$_1$}, A is given by:

$A_{11} = (1/2)(\lambda\{6,7\} + (1/2)\lambda_3)$,
$A_{12} = (1/2)\lambda$,
$A_{22} = -(1/2)\lambda\{8,9\} + (1/4)\lambda_{10} + (1/3)\lambda_{11}$.

- In the basis {hω^-, zω^-, (S S^-)$_1$, (S S^-)$_1$}, A is given by:

$A_{11} = A_{22} = (1/2)(\lambda\{6,7\} + (1/4)\lambda_1)$,
$A_{12} = 0$,
$A_{13} = A_{24} = (1/4)(\lambda_2 + \lambda_3)$,
$A_{14} = -A_{23} = (1/4)(\lambda_2 - 2\lambda_3)$,
$A_{33} = A_{44} = (1/2)(\lambda\{6,7,11\} + (9/4)\lambda_1 + \lambda\_\{8,9,10\})$,
$A_{34} = -(3i/4)\lambda_1$,
$A_{13} = A_{24} = (1/4)(\lambda_2 + \lambda_3)$,
$A_{14} = -A_{23} = (1/4)(\lambda_2 - 2\lambda_3)$.

2. Scatterings between states in 8-dimensional representation of the SU(3) group

In this case, the Clebsch-Gordan coefficients for the 8 representation are proportional to d_{$\alpha\beta\gamma$}, and those for the 8 representation are proportional to f_{$\alpha\beta\gamma$}. The values of these coefficients are:

$C^8[1] = (1/2\sqrt{3})\mathrm{diag}(1, 1, -2)$,
$C^8[2] = (1/2)\lambda_1$,
$C^8[3] = (1/2)\lambda_3$,
$C^8[4] = (1/2\sqrt{3})\mathrm{diag}(1, -1, 0)$,
$C^8[5] = (1/2)\lambda_2$,
$C^8[6] = (1/2)\lambda_3$,
$C^8[7] = (1/2)\lambda_1$,
$C^8[8] = (1/2\sqrt{3})\mathrm{diag}(1, 1, 1)$,

and similarly for the 8 representation with appropriate normalization factors.

- In the basis {$\omega^- S^+$, hS , hS , zS , zS , $(S^- S^+)_8$, $(S\ S\ )_8$, $(S\ S\ )_8$, $(S\ S\ )_8$, $(S^- S^+)_8^-$, $(S\ S\ )_8^-$}, the non-zero A are:

$A_{11} = (1/4)(\lambda_2 - 2\lambda_3)$,
$A_{12} = -A_{15} = i(1/4)\lambda_1$,
$A_{13} = A_{14} = (1/4)\lambda_{1,2}$,
$A_{16} = (1/4)(\lambda_2 + 2\lambda_3)$,
$A_{17} = A_{18} = (1/4)\lambda_{1,2}$,
$A_{22} = A_{55} = (1/2)(\lambda\{6,7\} + (1/4)\lambda_1)$,
$A_{23} = A_{36} = A_{46} = A_{59} = (1/4)\lambda_3$,
$A_{25} = A_{34} = (1/4)\lambda_3$,
$A_{29} = A_{36} = A_{46} = A_{59} = (1/4)(\lambda_{1,2} - \lambda_3)$,
$A_{33} = A_{44} = (1/2)(\lambda\{6,7\} + (1/4)\lambda_1)$,
$A_{37} = A_{48} = (1/4)\lambda_{1,2}$,
$A_{38} = A_{47} = (1/4)\lambda_{1,2}$,
$A_{66} = (1/2)(\lambda\{6,7,11\} + (5/4)\lambda_1 + \lambda\{8,9,10\})$,
$A_{67} = A_{68} = (1/4)\lambda_{1,2}$,
$A_{77} = A_{88} = (1/2)(\lambda\{6,7\} + (1/4)\lambda_1)$,
$A_{78} = (1/2)(\lambda\{8,9\} - \lambda_{10} - (3/4)\lambda_{11})$,
$A_{99} = -(1/2)\lambda_1 - (1/4)\lambda\{6,7,11\} - i(1/4)\lambda\{9,10\}$,
$A_{10,10} = A_{13,13} = (1/2)(\lambda\{6,7,11\} + (5/4)\lambda_1 + \lambda\{8,9,10\})$,

$A_{10,11}$ = -(3i/4)λ_1,
$A_{11,11}$ = (1/2)(λ_{6,7} + (1/4)λ_1).

- In the basis {ω^-S , ω^-S , hS^-, zS^-, (S S^-)$_8$, (S S^-)$_8$, (S S^-)$_{\bar{8}}$, (S S^-)$_{\bar{8}}$}, the non-zero A are:

$A_{11} = A_{22}$ = (1/2)(λ{6,7} + (1/4)λ_1),
A_{12} = 0,
$A_{13} = -A_{24}$ = i(1/4)λ_1,
$A_{14} = A_{23}$ = (1/4)(λ_2 - 2λ_3),
$A_{15} = A_{26} = A_{36} = A_{45}$ = (1/4)(λ_2 + 2λ_3),
$A_{18} = -A_{27}$ = (1/4)(λ_2 + 2λ_3),
$A_{33} = A_{44}$ = (1/2)(λ{6,7} + (1/4)λ_1),
$A_{38} = A_{47}$ = i(1/4)(λ_2 + 2λ_3),
$A_{55} = A_{66}$ = (1/2)(λ{6,7,11} + (9/4)λ_1 + λ{8,9,10}),
A_{56} = -(3i/4)λ_1,
$A_{57} = A_{68}$ = i(1/4)(λ{6,7,11} - λ{9,10}),
$A_{58} = -A_{67}$ = (1/4)(λ_2 - 2λ_3),
$A_{77} = A_{88}$ = (1/2)(λ{6,7,11} + (9/4)λ_1 + λ{8,9,10}),
A_{78} = -(3i/4)λ_1.

3. Scatterings between states in 10-dimensional representation of the SU(3) group

In this case, the Clebsch-Gordan coefficients are given by appropriate matrices with normalization factors (detailed expressions omitted for brevity, following the pattern of the 8-dimensional case).

- In the basis {(S^-S^+)$_{10}$, (S S)$_{10}$}, A is given by:

$A_{11} = A_{22}$ = (1/2)(λ{8,9} - λ_{10}),
A_{12} = -i(1/2)λ{9,10}.

- In the basis {(S^-S^+)$_{\bar{10}}$, (S S)$_{\bar{10}}$}, A is given by:

$A_{11} = A_{22}$ = (1/2)(λ{8,9} - λ_{10}),
A_{12} = -i(1/2)λ{9,10}.

- In the basis {(S S^-)$_{10}$, (S S^-)$_{10}$}, A is given by:

$A_{11} = A_{22}$ = (1/4)λ{- - -} + (1/2)λ_8,
A_{12} = i(1/4)λ{- - +}.

- In the basis {(S S^-)$_{\bar{10}}$, (S S^-)$_{\bar{10}}$}, A is given by:

$A_{11} = A_{22}$ = -(1/4)λ{- + +} + (1/2)λ_8,
A_{12} = -i(1/4)λ{- + -}.

4. Scatterings between states in 27-dimensional representation of the SU(3) group

In this case, the Clebsch-Gordan coefficients are given by appropriate matrices (detailed expressions follow similar patterns as above).

- In the basis $\{(S^-S^+)_{27}, (S\ S\ )_{27}, (S\ S\ )_{27}\}$, A is given by:

A_{11} = (1/2)(λ{6,7,11} + λ{8,9,11} + λ_{10}),
A_{12} = A_{13} = (1/2)λ_{10},
A_{22} = A_{33} = (1/2)(λ{6,7,11} + λ{8,9,10}),
A_{23} = -(1/2)λ_{8,9,11} + λ_{10}.

- In the basis $\{(S\ S\ )_{27}\}$, the S-partial wave amplitude for scattering $(S\ S\ )_{27}$ $\to$ $(S\ S\ )_{27}$ is:

A_{11} = (1/2)λ{+ + +} + λ{6,7,8,9}.

- In the basis $\{(S\ S^-)_{27}, (S\ S^-)_{27}\}$, A is given by:

A_{11} = A_{22} = (1/4)λ{+ + + +} + (1/2)λ_8,
A_{12} = i(1/4)λ{+ + - -}.

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Note: Figure translations are in progress. See original paper for figures.